Effect of FSW on the Mechanical Properties and Microstructure of 6082-T6 AA

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Abstract.
This paper reports the effect of Friction Stir Welding on the mechanical properties and microstructure of 6082-T6 Aluminium alloy. The welds were produced using three different transverse speeds of 90, 120 and 150m/min to vary the heat input to the wields. The rotational speed of 750rpm is constant for the three welds samples, plunge depth of 0.31mm and tool tilt angle of 3 degrees was employed. The mechanical properties were characterised by the tensile analysis, the microhardness and joint efficiency of the welded interface. The microstructures, macrostructures, fracture surface and grain sizes were characterised. The result revealed that tensile strength at the joint interfaces of the three samples was enhanced as the transverse speed increases from 90m/min to 150m/min. The joint efficiency of the joint interfaces of the three welded samples increases. The Vickers hardness values at the joint interfaces were enhanced for the three samples when compared with the base material. This is attributed to the strain hardening phenomenon. The resulting microstructural characterization shows that good metallurgical bonding was achieved at the joint interfaces of the welds produced, this is evident with the presence of the transition region separating the advancing side from the retreating side of the joint interfaces.

Keywords: Friction Stir Welding, Heat Input, Joint Efficiency, Microstructure, Mechanical Properties

1. INTRODUCTION
Friction Stir Welding is a solid state welding process invented and patented by the Welding Institute (TWI) in the United Kingdom in 1991. It is increasingly popular and welcomed among manufacturing industries especially in the aerospace, automotive, ship and container industries because of its unique benefits such as environmentally friendly, energy efficiency and adaptability of the process to different applications. The process initially was invented for butt and lap joining of ferrous and non-ferrous and plastics, but its applications and scope has now been enlarged and accommodated other various materials[1]-[3]. The applications of FSW to the different manufacturing process are expected to continue to grow because of its immense benefits. The process is very simple but continuous; it involves plunging a non-consumable tool between the joint interface of the two sheets or plates to be welded. The tool traverses along the joint line at a set rotational speed and feed rate, at the end of the weld the tool is retracted from the weld. The relative motion between the tool and the substrate generates frictional heat that creates a plasticised region around the immersed portion of the tool - pin. The shoulder, in addition, prevents the plasticized material from being expelled from the weld. Hence, as the tool traverses along the joint line, it forces the plasticised material to coalesce behind the tool to form a solid phase joint [2][6]. The ability of FSW to generate heat internally for the plastic deformation of the materials at the sir zone uniquely differentiate friction stir welding from other traditional welding processes. The applications and studies into friction stir welding since over the last three decades have proven that it can be employed to weld any materials provided the tool can withstand the extreme heat generated during the process. The weld problems associated with conventional welding are not associated with FSW process. Literature confirmed and identified Aluminium as one of the materials that can be welded easily through FSW. However, the challenge is welding Aluminium alloys grades from the 1xxx to 7xxxx series with conventional welding process though it can be used to weld pure aluminium easily.

A schematic of FSW process is shown in Figure 1 with a similar joint in Butt configuration.

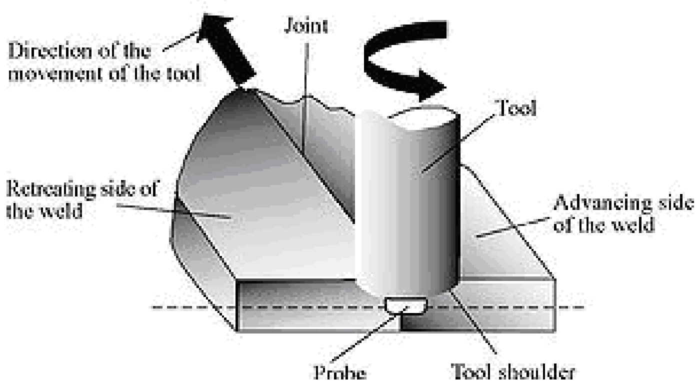

Figure 1: Schematic of Friction Stir Welding [4]

Considering the successful joining of the 3mm aluminium alloy, which finds applications widely in modern industries. The evolving mechanical properties and microstructure become very interesting to investigate to establish possible application of the welded component.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials

The aluminium alloy of 5mm thickness was selected for the butt joint using FSW process, were machined into the weld coupon on 110 x 54mm2. A concave threaded tool made from H13 tool steel was used for the welding of the aluminium sheet. A constant rotational speed of 750rpm, varied transverse speed (90, 120, and 150mm/min), a tool tilt angle of 3 degrees and a plunged depth of 0.31mm were employed.

2.2. Mechanical Test

The tensile test samples were prepared according to the ASTM standard, three sets of test samples were machined to 20 x 60mm2 (samples A, B & C). The sets of the machined samples are presented in Figure 2. The test was conducted with instron 1195 universal testing machine with a load cell of 100kN.

Figure 2: Machined welded tensile test samples A, B & C

The Vickers microhardness test was conducted using hardness indenter. The test samples for hardness were machined to 7 x 25mm2, mounted, ground and polished. The hardness profile of the welded was across the thickness based on the ASTM standard E384 2011. A load of 250g was applied for 15 seconds at constant interval if 1mm.

2.3. Microstructural Evolution

The resulting weld microstructures were characterized through the optical microscopy and SEM. The metallographic samples were prepared based on the ASTM standard E3, 2011, hot mounted in polyfast resin, ground and polished, and etched by immersing the samples in Polton’s reagent to reveal the grain structure of the microstructure.

3. RESULTS AND DISCUSSION

3.1 Weld Physical Appearance

Representative samples of the welded joints are shown in Figure 2. Sample A produced at 90 mm/min shows a good appearance with minimum flash, sample B surface appearance also looks good but with more flash. Sample C also has a fairly good surface appearance but with more flash along the side and at the end of the weld length. The visual inspection of the three samples shows that the welds are free from surface cracks.

Figure 3: Physical appearances of Butt weked samples A, B & C

3.2 Tensile Testing

The tensile fracture samples are shown in Figure 4. It was observed that the fractured zone for the three samples is some distance from the joint area. Sample A1 welded at 90mm/min has the fracture close to the retreating side, while for sample B1 welded at 120mm/min, the fracture occurs closer to the advancing side.

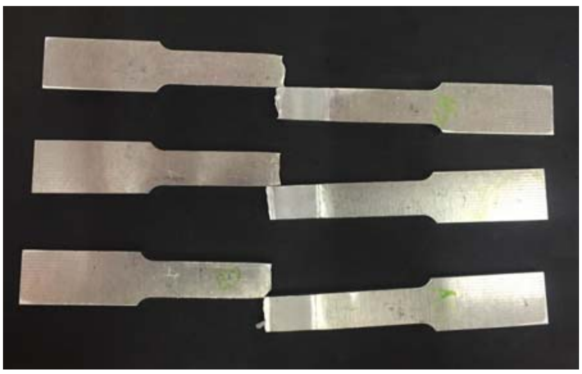

Figure 4: Fractured tensile samples

The results of the stress-strain showing the behaviour of the materials are shown in Figure 5. A reduction in Ultimate Tensile Strength was observed from the base value of 315MPa when compare to values of the welded samples shown in Figure 6. Among the three sets of samples A, B & C, sample C with a rotational speed of 150mm/min has a corresponding Ultimate Tensile Strength which has been attributed to the thermal cycles that occurred in the material. A low Ultimate Tensile Strength was observed for sample A with the lowest rotational speed of 90mm/min. The trend, therefore, shows that the Ultimate Tensile Strength of the welded samples decreases as the rotational speed decrease. Similarly, the percentage elongation ranges between 45-5.5% and sample C with the highest on an average value.

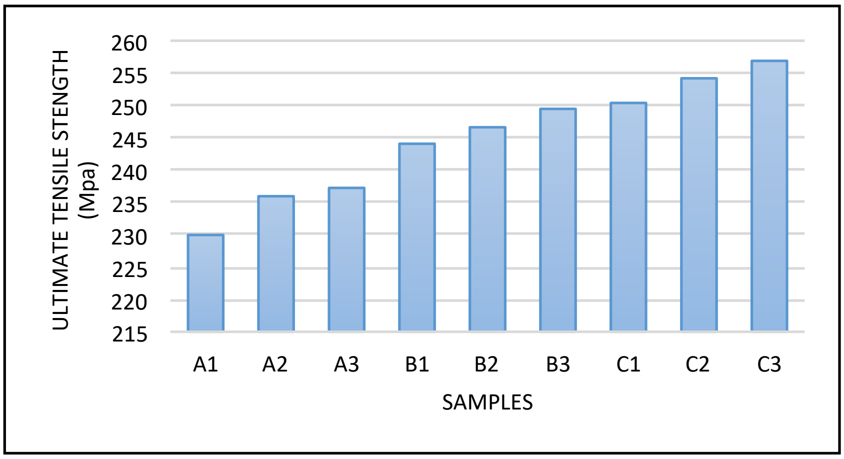

Figure 6: Ultimates Tensile Strength of welded samples

3.3 Vickers Microhardness

The Vickers Microhardness profiling for the three samples is shown in Figure 7, with the stirred zone corresponding to the centre point 10 on the distance axis. The hardness profiling for sample A with a rotational speed of 90mm/min shows an increase in hardness at the stirred zone/ nugget, which is due to the strengthening properties that arise from the weld. It was found that the next region, which is the TMAZ, there is a slight decrease in the hardness value. This may be attributed to the thermal effects of the tool on the material decreasing the hardness. Further away from the NZ is the HAZ where the lowest hardness value was recorded for all the samples in this research study.

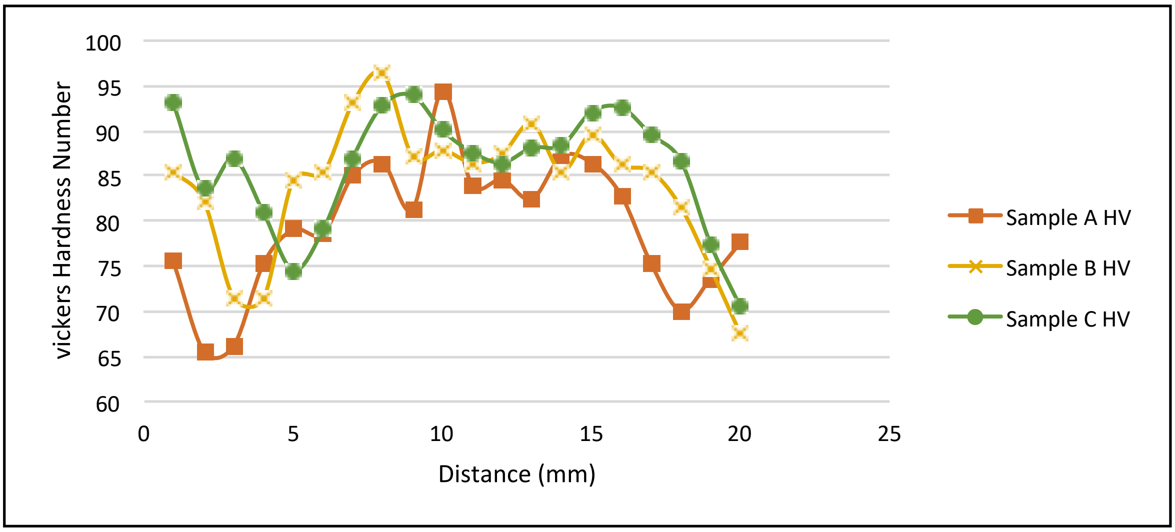

Figure 7: Vickers Hardness Profile for the three welded 6082-T6 AA

The microhardness profiling for sample B shows a slight shift to the left with the highest hardness value being slightly between the NZ and the TMAZ. The NZ region of this sample shows linearity in the NZ an almost constant hardness value across the region. The profiling of this sample is not symmetrical about the nugget zone. On the left side of the sample in the HAZ the material experiences the second lowest hardness value. On the right side of the sample between the TMAZ and HAZ, there appears to be a steady decrease in the hardness profiling of the sample right to the edge of the sample with the lowest hardness value of the sample. The hardness profiling of sample C follows no trend. The highest hardness value observed is the base material of the weld as well as the NZ; the hardness values are almost the same. Thus, indicating that the integrity of the hardness of the material was maintained. However, on the left side of the material, there is a decrease in the hardness value in the TMAZ region, this may be a result of the thermal effects on the material. In the HAZ on the left side, the hardness value increased from the TMAZ to the HAZ, with a further increase to the base material. On the right side of the sample, the TMAZ experiences an almost constant hardness value, which increases slightly into the HAZ with a decreasing parabolic profile, with the lowest hardness value of the sample.

Furthermore, a relationship between the fractured zone of the tensile samples and the hardness values show a correlation. The fracture occurred on the advancing side of the samples, which is the softer side of the material. On the other hand, it was observed that the lowest hardness values are on the advancing side of the material. The lower hardness values are attributed to the stirring of the tool pin as well as the selected process parameters.

3.3 Microstrutural Evolution

The micrograph of the fracture zone is shown in Figure 8. The results obtained from the SEM analysis are similar to the micrograph of the base material because the fracture occurred after the welded region. The results obtained, revealed varying ductility across the fracture of the surface. It was observed that the dimples on the image vary in sizes. However, most of the surface is covered with large dimples and smaller dimples located in between the large dimples. Thus, the area with the small dimples relates to the high density of the material reviewed.

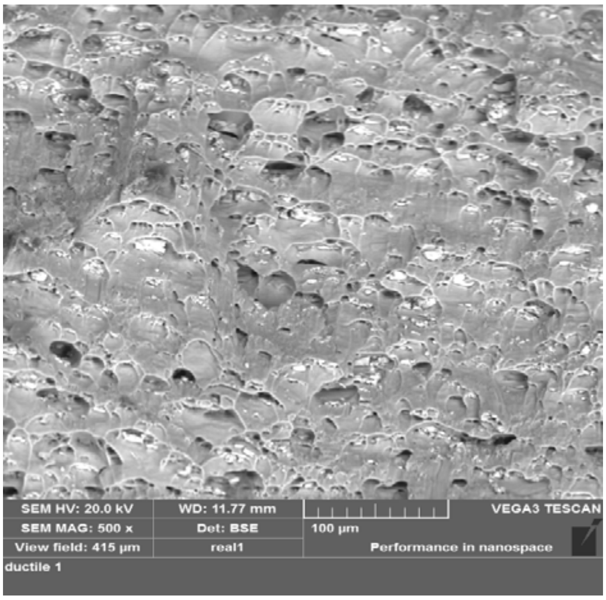

Figure 8: Typical micrograph of the fracture location

The properties of processed materials are often affected by the employed process, and in particular, Friction Stir Processed or Welded materials are affected primarily by the tool geometry, hence, the morphology of the weld. It was observed that there exist a relationship between micro and macro structures as defined by the partitioned zones from the evolved structure of the material. The three identified zones are the Stir Zone/Nugget, Thermomechanically Affected zone (TMAZ) and the Heat Affected Zone. The base metal is often the zones not affected by the generated heat of the process. The microstructural evolution of the weld is shown in Figure 9 with the variations of the microstructural zones, discussed.

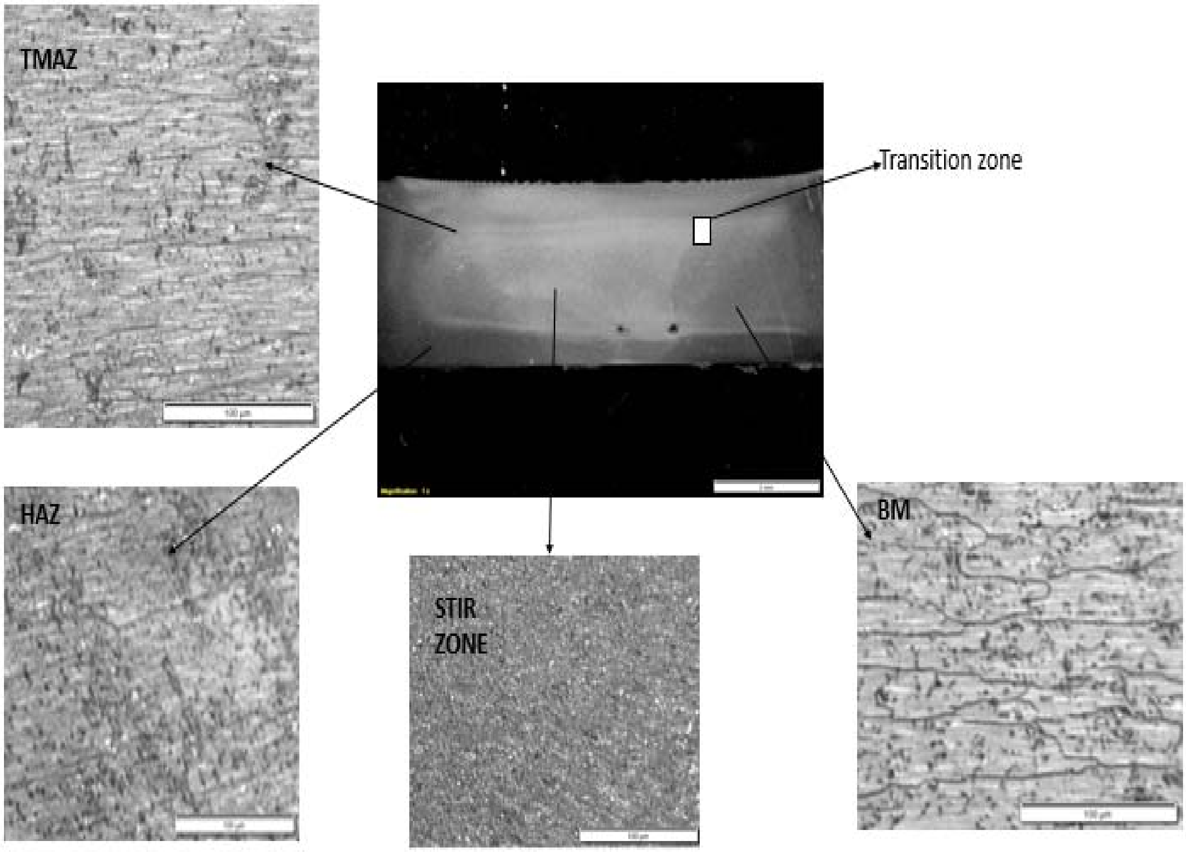

Figure 9: Microstructural evolution of the welded samples (a) BM, (b) HAZ, (c) TMAZ and (d) NZ

The first observation under the microscope was the base material and the HAZ. These are two regions farther from the welded region of the sample. The BM provided a reference view of the grain sizes before the welding process. The grain sizes observed for the sample were elongated. The grain sizes observed in the HAZ are similar to the elongated grain sizes of the BM. However, due to the heat of the weld, the grains appear slightly overgrown. The TMAZ region was subjected to more heat because it is closer to the centre of the weld, where the material experienced dynamic deformation resulting in elongated and rotated grains due to the strain in which the material was subjected to. The Stirred Zone being the centre of the weld where the material was subjected to the most FSW forces. The fusion of the materials occurs in this region as a result of the heat generated, the material experienced dynamic recrystallization, which resulted in fine small grains. This is attributed to the increased strain at the elevated temperature during the process and the properties characterised are excellent ductility, improved mechanical properties and residual stresses.

4. CONCLUSIONS

The FSW of Aluminium AA6082-T6 sheet was successfully joined with the following properties constant - transverse speed, tool tilt angle and plunged depth, three sets of rotational speeds were varied at 90, 120 and 150mm/min. The welded joints were further characterised through the mechanical tests and microstructural evaluation. The joints produced were free of major weld defects. However, the process can be further optimised to improve the joint integrity. The Micro Vickers hardness was observed to increase at the Nugget Zone as the rotational speed increases across the three sets of welded samples. Similarly, both the Ultimate Tensile Strength and percentage elongation increases as the rotational speed increases. The grains at the Stirred Zones across the three welded samples were crystalised and equiaxed grain structure, which is attributed to both the static and dynamic recrystallization.

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